BELLCOMM, INC.
1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: Optical Data Processing and Terrain-Hazard Analysis of Lunar Orbiter Photographs
Case 340

DATE: May 8, 1967

FROM: V. B. Schneider

ABSTRACT

This paper presents some suggested alternatives to the use of digital computers in the numerical processing of lunar photographs. Newly developed techniques of optical data processing, which have much greater data-handling capacity and speed than is obtainable from digital computers, are suggested for promising applications, such as noise filtering and detection of spacecraft-landing obstacles in lunar photographs. Further applied research is recommended for the purpose of achieving a practical implementation of these processing techniques.

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MEMORANDUM FOR FILE

I. INTRODUCTION

The objective served by photographing the moon in the Lunar Orbiter missions is to provide detailed information about the terrain in selected areas of the moon. In each such photograph, certain numerical processes must be performed in order to make intelligent use of the data contained in it. First, the images must be compensated for the loss of high-frequency details caused by the camera telephoto lens. In order to use the photographs for constructing lunar maps, photometric nonlinearity and distortions must be corrected and the photometric function must be used to convert image brightness to lunar surface slope. In addition, it is desirable to devise rapid and automatic methods of comparing lunar terrains on the basis of their hostility to spacecraft landings.

The reason for considering optical techniques of numerical processing can be illustrated by a simple example: In the processing of Ranger lunar photographs by computer, sophisticated picture correction methods take about 15 minutes of computer time per picture. In a typical Ranger photograph, there are about 10^6 points of data. In a Lunar Orbiter photograph, there are about 10^9 points of data. Thus, to process a Lunar Orbiter photograph by Ranger methods would take 1000 times as long--about 250 computer hours per image. Because of the large number of Lunar Orbiter photographs, some alternative data-processing scheme, not subject to the relative slowness of computers, would permit quantitative analysis of much more of the available data.

It is for this reason that optical data processing (ODP) is considered. Essentially, ODP is an analogue technique whose only speed limitation is related to the time required for developing photographic emulsions. Much of the technology of ODP can be understood by analogy to the techniques used in designing analogue filtering devices in electrical engineering. Earlier techniques of electrical filter synthesis were concerned with the design of filters for one-dimensional (electrical) signals. By distinction, ODP is concerned with the synthesis of filters for two-dimensional signals like photographic images.

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In this paper, two types of image processing are discussed. Under the heading of "corrective masks" appear two image-compensation techniques whose plausibility was recently suggested.* These corrective masks are for the purpose of brightness compensation of lunar photographs from the effects of vignetting** in the Ground Recording Equipment and from variations in brightness levels over the photographed lunar scenes. Under the heading of "spatial filtering masks" appear suggestions involving linear filtering operations on photo images that would otherwise be performed by digital filtering. In particular, the design of two-dimensional noise suppression filters for lunar photographs is considered. Also, a scheme for pattern recognition of spacecraft landing obstacles by filtering of lunar photographs is presented. With a moderate research effort, it is believed that these techniques could be implemented to produce results comparable to, and more rapid than, what could be achieved by a digital computer for the same data format.

II. BACKGROUND

A selected bibliography of papers in the ODP and optical filtering field appears at the end of this memorandum. Rather than rehearse basic theoretical results which have appeared in well-written review articles,[4,5] we presuppose some knowledge of ordinary Fourier transform theory. In what follows, one can bear in mind the picture of an ODP system as a simple optical bench consisting of a laser or mercury arc, assorted lenses, an "input plane" in which the photographic plate to be processed is placed, a "Fourier plane" in which is placed the photographic representation of an optical filter, and an "output plane" in which is located an unexposed sheet of film that receives the processed image. Much of the analogy between one-dimensional electrical filters and two-dimensional optical filters will be evident in what follows. Our purpose in presenting the suggested techniques, as well as schemes for implementing these techniques is to show how much of the current state-of-the-art can be used for implementing our suggestions.

III. CORRECTIVE METHODS

A. Multiplicative Corrections

In the Lunar Orbiter image framelets, a pronounced vignetting effect caused by the spacecraft line scan tube and

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*The suggestion occurred at a conference with people from Tech/Ops, Inc., Burlington, Massachusetts.

**Vignetting is a multiplicative variation in intensity across the image.

the Ground Recording Equipment is visible. This vignetting arises from intensity variations in the light beams scanning the framelets, and is a multiplicative effect. By comparison of framelets from the received "Goldstone leader" image* with portions of the original image in our possession, a two-dimensional array of correction factors could be calculated. Since the same vignetting appears on every framelet, a standard correction mask could be prepared from this calculated array of corrections. The mask would consist of a film plate whose optical transmission as a function of its coordinates is proportional to the corresponding array of correction factors.

To correct some framelet that displays vignetting, the framelet and mask are aligned in proximity, and a beam of light is shined through the two pieces of film. The composite image is thereupon corrected for vignetting and can be focused onto an unexposed sheet of film. Alternatively, an image of the correction mask is projected onto an uncorrected framelet. The resultant illuminated image is then projected onto an unexposed sheet of film.

Assuming careful control of such factors as film positioning, dimensional accuracy of the images, and film exposures, this correction method is as accurate as computer processing. A suggested method of synthesizing the compensating mask involves the use of an isodensitometer tracing to generate a "half-tone" compensating function to be reduced by photography onto a sheet of film.**

B. Standardization of Image Brightness

Another possible use for a compensating mask is as a photometric function standardization device for Lunar Orbiter images. For a given lunar image having a known distribution of surface illumination and observation angles, a computer program could compute an approximate compensation mask. If the variation of the photometric function over the lunar surface in the image is sufficiently slow, a considerable savings of labor is obtainable by computing the mask compensating factors on a regional basis rather than point-by-point. Such a method offers greatest potential for quick processing of high-resolution lunar photography, where the assumptions are most valid and extremes of accuracy are not needed.

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*The leader has uniform density fields.

**Private communication, Dr. L. Kofsky, Tech/Ops, Burlington, Massachusetts.

A photographic image compensated by this process has a brightness distribution that is an almost uniform, nonlinear function of surface slope. One step remains to prepare such an image for processing by further analog techniques. By optical means, the compensated image is transformed geometrically so that the photometric planes are in the x-direction of an x-y coordinate system.

In our scheme, the resulting image can next be scanned by a high-resolution facsimile machine in the x-direction of the image coordinate system. The electrical signal from each scanned line of the image is passed through an appropriate nonlinear network whose transfer function compensates for the lunar photometric function. In the resulting image signal, brightness is proportional to ground slope.* Such a processed image is useful for purposes of terrain mapping and for automatic analysis of spacecraft landing hazards, as will be seen later.

IV. SPATIAL FILTERING MASKS

In much of the current ODP technology, spatial filtering masks take the form of special-purpose diffraction gratings inserted in the "Fourier plane" of an optical bench of the type described earlier. The design of these masks is a well-understood technology, as evidenced by current journal articles.[1,2,4,9] These articles describe various methods, ranging from special computer programs which draw the gratings[1,2] to special optical interferometers which photograph the gratings on a sensitized plate.[4,9] In these latter methods, an arbitrary photograph is inserted in the interferometer, a light source is turned on, and the grating appears on the sensitized plate at the output of the device.

The Fourier transforms realized by these gratings can be multiplied and added together optically to form specialized two-dimensional filters. The multiplication is accomplished by cascading optical benches to obtain multiple Fourier planes so that the spatial filtering masks can be multiplied optically. Examples of transfer functions useful in processing Lunar Orbiter photographs will be given in what follows.

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*If an integrating circuit were added after the nonlinear network, the resultant image signal would be proportional to elevation.

A. Noise Compensation and Contrast Enhancement of Imagery

A basic problem in reproduction of Lunar Orbiter photographs is that the characteristics of the image transmission system are not entirely predictable in advance. Important examples of this phenomenon are the additive noise and image degradations arising from the spacecraft camera lens film modulation transfer function. In the design of compensating filters for these degradations, one piece of information has not yet been supplied: the exact nature of the two-dimensional power spectrum of the original image signal is unknown. These considerations affect the design of filtering devices for processing Lunar Orbiter imagery.

In Appendix A appears a suggestion for designing near-optimal Wiener filters to compensate lunar photographs. The design of these filters is based on certain assumptions about the statistical nature of the two-dimensional brightness power spectra of lunar photographs. These assumptions have yet to be verified or modified empirically. As an alternative to the approach in Appendix A, we present here an optical spatial filter realization of a filtering scheme already proved successful on the earlier Ranger photographs.

The method used to design a digital filter for the earlier Ranger photographs can be described as follows:[13] we use the notation $\underline{w} = (w_x, w_y)$ to denote spatial frequency coordinates in the space of two-dimensional Fourier transforms. A given photograph has a brightness distribution $B(\underline{r})$, with $\underline{r} = (x,y)$ the coordinates of points in the image. Let $T(w)$ be the lens film modulation transfer function of the spacecraft camera under analysis. Let $\underline{w}_c$ be the cutoff frequency of this lens film system. Then, the form of the digital filter used to compensate the Ranger photographs is as given in (1):[13]

$$
\begin{aligned}
T'(\underline{w}) &= \frac{1}{T(\underline{w})} \qquad \text{for} \qquad ||\underline{w}|| \leq ||\underline{w}_c|| \\
&= \frac{1}{T(\underline{w}_c)} \qquad \text{for} \qquad ||\underline{w}|| > ||\underline{w}_c||
\end{aligned}
\tag{1}
$$

In the original digital filter realization of (1), $T'(\underline{w})$ is inverted to give an impulse response $T'(\underline{r})$, that is numerically convolved with the image brightness signal $B(\underline{r})$.

In an ODP system, a filtering mask corresponding to $T'(\underline{w})$ can be constructed, and then used in an optical bench to process photographs in batches. For such a processing scheme, only times of exposure and film developing limit speed, and great economies of time can be realized by operating several optical benches simultaneously. For the computer, on the other hand, each of the 10^9 points in a lunar image must be operated on in sequence by the system function $T'(\underline{r})$. For large numbers of photographs, the optical method seems more rapid.

B. Detection of Camera Misfunction

In this section, we suggest an empirical method of detecting the causes of possible Lunar Orbiter camera misfunctions. The principal rationale used in detection is based on the following observations: image-motion blur is an invertible (linear) operation on the image when caused by any image displacement over the film in which the image does not move back over itself. Thus, the combined effects of uniform and nonuniform motions in several directions can be analyzed by Fourier transform theory, so long as the combined motion satisfies the above condition.

The following discussion gives the Fourier transforms of several representative types of image blurring. The importance of discussing these transforms arises from the following fact: in an optical filtering bench such as the type described earlier, it is possible to insert a sensitized plate in the Fourier plane. When a transparency is placed in the input plane and the light source is turned on, an image $P(\underline{w})$* appears on the plate in the Fourier plane. The brightness distribution on this plate is proportional to the modulus of the two-dimensional Fourier transform of the plate in the input plane. Thus, this arrangement permits instant spectral analysis of lunar images.

The Fourier transforms of the various types of uniform and nonuniform blurs exhibit a periodic effect arising from the finite width of the blurring intervals. As one example, the transform $T_1(f)$ of linear motion blur is given as

$$|T_1(f)| = \frac{\sin(\pi fc)}{\pi fc} \tag{1}$$

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*$\underline{w} = (w_x, w_y)$ is the coordinate of a point on the image in a rectilinear coordinate system.

(Here, c is the width of the blurring interval and f is the spatial frequency along the direction of blur.) For the next order of motion blur, involving constant acceleration of the image over the film, the associated Fourier transform $T_2(f)$ is of the form

$$T_2(f) = \frac{2}{j2\pi fc}\left(\frac{1-e^{-j2\pi fc}}{j2\pi fc}\right) - \frac{2}{j2\pi fc}\, e^{-j2\pi fc} \qquad (2)$$

For the case of double imaging, where two identical images are recorded, one displaced c units from another, the associated transform $T_3(f)$ is given by

$$|T_3(f)| = \cos(\pi fc) \qquad (3)$$

The periodic effects of the $\sin(\pi fc)$ terms in (1) and (2) are manifested by regularly spaced dark bars of width (1/c) cpmm. in the Fourier transform photograph of the image described earlier. The dark bars arise from the negative-valued intervals of $\sin(\pi fc)$ in (1) and (2), that do not register on photographic emulsions. For type (2) blur, the assumptotic behavior of the transfer function is of particular interest:

$$\lim_{f\to o} |T_2(f)| = 1 \qquad (4)$$

$$\lim_{f\to\infty} |T_2(f)| = \frac{1}{\pi fc} \qquad (4a)$$

For type (3) blur, alternate grey bands are visible in the Fourier spectrum, with intensity peaks spaced (1/c) cpmm. apart.

One limitation to this detection scheme results from the necessity of counting intensity minima on the Fourier transform of some blurred image. If the extent of this misfunction is too small, i.e.,

$$(fc) << 1 \qquad (5)$$

for f below the cutoff of the lens film system, no zeroes will appear in the Fourier transform of the images, although the high-frequency information in the images may still be degraded.*

In general, the Fourier transform of an image suffering from several kinds of blurring motion in more than one direction will exhibit a variety of regularly spaced black lines. The distance between these lines provides a measure of the interval over which the blur occurs. The orientation of these lines betrays the directions in which blurring originally occurred. Once the effects of the lens-film modulation transfer functions are compensated for, a quantitative estimate of the high-frequency envelope of the blur transforms can be obtained from the resulting Fourier transform of the image. One, or possibly several, models depicting the cause of the blur can then be constructed. From these models, compensating masks for the image can be designed. The mask which appears to provide the best image restoration then corresponds to the best guess as to the origin of the blur.

C. Suppression of Framlet Lines

For purposes of optical inspection and stereoscopic analysis, it is desirable to construct composite Lunar Orbiter images in which a cluster of framelets compose an image of a lunar scene. In all photographs constructed from framlets, a pattern of black lines is visible between the framlet edges. This pattern hinders stereoscopic inspection of pairs of low resolution images. By use of optical techniques, it is a simple matter to synthesize a bandstop spatial filter that will suppress the optical spectrum of these black lines.**

The amount of processing time involved in filtering these lines from an image is negligible, since the same filter can suffice for all lined images. Indeed, one could conceive of an optical viewer incorporating the spatial filter for line suppression as part of the optics.*** Where it is desirable to avoid suppression of all vertical lines in a processed image, the

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*Private communication, Dr. Paul Roettling, Cornell Aeronautical Laboratories, Buffalo, New York.

**The author has recently learned that engineers at Cornell Aeronautical Laboratories have succeeded in doing just this.

***Similar devices have been in use since 1905, when Leitz introduced a student microscope with removable enhancement filters.

spatial filter can be designed to suppress a particular pattern of lines, such as the pattern produced in an image composed of nine framelets.

D. Automatic Detection of Spacecraft Obstacles and Craters in Lunar Imagery

In the photograph of a lunar terrain is a class of objects of a particular size, shape, and orientation, whose presence is to be detected mechanically. For this section, we take craters as the example of a class of terrain features to be discovered. To detect these objects by optical spatial filtering, it is necessary to standardize the image brightness so as to compensate for variation in sun angle and gross changes in lunar surface slope over a photographed terrain. Methods such as those described in section (III, B) are recommended for this task.

Given the brightness-corrected photograph of a lunar scene, we superimpose a coordinate system, with $\underline{r} = (x,y)$ as typical coordinates of a point. With such a standardized photograph, it is possible to consider the brightness distribution $B(\underline{r})$ as a sum of components:

$$B(\underline{r}) = \sum_i k_i D(r - r_i) + F(\underline{r}) \qquad (1)$$

Here,

$$o < k_i \leq 1 \qquad (2)$$

In (1), $\underline{r}_i$ is the coordinate locating the ith object whose brightness distribution is given by $D(\underline{r})$. Since $D(\underline{r})$ is a class of craters in this example, the constants k_i in (2) are used to indicate craters of varying depths in (1). Thus, for $k_i > k_j$, we say that crater i is deeper than crater j in the image, and therefore produces a stronger signal. The signal $F(\underline{r})$ is a combination of noise and surface features not characterized by $D(\underline{r})$.

In what follows, two spatial filters are to be constructed. The first filter is a bandpass filter that allows the spectra of our craters to pass and suppresses all other spatial frequencies. The second filter is a so-called matched filter of the sort that has been used in experiments for recognizing the presence and location of words in printed text.[9] In between these two filters will be a system that only permits images exceeding a certain brightness to be seen.

As we will show, the threshold system will emphasize all images passed to a uniform brightness level, and will suppress all images below its threshold of tolerance. The threshold image modulation θ is selected so that, for $k_i \geq \theta$ the image of a crater of modulation index k_i is transformed into a crater image of modulation k_i', where

$$k_i' = 1 \quad .$$

Thus, the threshold system transfers the filtered version of $B(\underline{r})$ into $B'(\underline{r})$, with

$$B'(\underline{r}) = \sum_i D(\underline{r} - \underline{r}_i) + F'(\underline{r}) \tag{3}$$

for all i such that

$$k_i \geq o \quad .$$

Here, $F'(\underline{r})$ is what is left of $F(\underline{r})$ after passage through the crater bandpass filter and the threshold device.

We now describe one method for constructing the filters: the first step is to construct $D(\underline{r})$, the brightness distribution of the crater whose presence is to be detected. A scale model of the crater can be constructed. The scale model is illuminated to simulate the lighting and viewing conditions in the image to be processed. A photograph of the model is taken. The model has been positioned in the center of its photograph with the same orientation and illumination as the object to be detected in the lunar image. The two spatial filters can now be constructed from this photograph, whose brightness distribution is given by $D(\underline{r})$.

We first indicate how a crater bandpass filter could be constructed for $D(\underline{r})$. An optical bench can be set up with the image $D(\underline{r})$ in the input plane and a sensitized plate in the Fourier plane. It will be recalled that the image of $D(\underline{r})$ in the Fourier plane is the magnitude of its two-dimensional Fourier transform. Thus, the image exposed on the sensitized plate will have a brightness distribution $|D(\underline{w})|$, where $D(\underline{w})$ is the transfrom of $D(\underline{r})$ and $\underline{w} = (w_x, w_y)$ is the vector frequency in the transform image. The developed negative plate now is a <u>bandstop</u> filter for the image of $D(\underline{r})$. To produce a <u>bandpass</u> filter for $D(\underline{r})$, we contact print the image $|D(\underline{w})|$ onto a high-contrast plate emulsion. The resulting photographic plate corresponds to a filter that passes all frequencies that occur in $D(\underline{w})$ and suppresses all other frequencies.

We next construct the matched filter for $D(\underline{r})$. This filter is nothing more than a grating which realizes the amplitude and phase components of $D(-\underline{w})$, the transform of $D(-\underline{r})$. The grating is constructed by placing the rotated image of $D(\underline{r})$ on the input of a suitably arranged optical interferometer.[9] We can next see what the effect of the matched filter is on the bandpassed, thresholded signal $B'(\underline{r})$ given in (3).

The effect of the matched filter is seen most easily by considering $B'(\underline{w})$, the transform of $B'(\underline{r})$. $B'(\underline{w})$ is represented in (4) as follows:

$$B'(\underline{w}) = \sum_i D(\underline{w}) \exp[-j\, \underline{w} \cdot \underline{r}_1] + F'(\underline{w}) \qquad (4)$$

Passing signal $B'(\underline{r})$ through the matched filter grating on an optical bench yields an output signal $o(\underline{r})$ whose transform is*

$$O(\underline{w}) = |D(\underline{w})|^2 \sum_i \exp[-j\, \underline{w} \cdot \underline{r}_i] + D(-\underline{w})\, F'(\underline{w}) \qquad (5)$$

The inverse transform of $|D(\underline{w})|^2$ is simply the autocorrelation function of $D(\underline{r})$. Thus, the first term in (5) appears as a

*Note: $D(-\underline{w})$ is the complex conjugate of $D(\underline{w})$.

configuration of bright spots of light* in the image $O(\underline{r})$. These bright spots are located where each crater to be detected in the original image occurred. The second term in (5) is simply the cross-correlation function of $D(\underline{r})$ and $F'(\underline{r})$ the noise and clutter field, which yields a random scattering of low-intensity light blobs in the image of $O(\underline{r})$.

We can measure or calculate in advance the width of the crater spots that appear in $O(\underline{r})$, as well as the brightness that results from the thresholding and correlation operations on the craters. With this knowledge, we have a reliable and rapid means for automatically detecting the number and location of craters in a lunar photograph. It should be noted that a single filter will match to craters of only one diameter.

V. CONCLUSION

At present, it seems doubtful that optical data processing (ODP) can give accurate and rapid computations of such information as photometrically derived altitude profiles. This limitation stems from the nature of ODP, which permits large volumes of standardized linear operations on input data, but has no capability for arithmetic computations and "local correction" programs. Thus, in applications where large volumes of predetermined linear operations must be performed, ODP is incomparably faster than conventional computer processing. For applications that call for specialized operations on one set of data, in which time-varying corrections are determined from another set of data, ODP is awkward to use at best. In comparable situations, ODP offers potentially the same accuracy and linearity as computer processing,[8] at much lower processing cost.

The suggestions in this memorandum are largely for the purpose of obtaining rapid alternatives to computer processing. In particular, for the problems of obstacle detection and crater counting, both pattern recognition problems, this memorandum offers a scheme for direct image processing in which the input is an uncorrected image and the output is an image with only the objects whose presence and number are to be determined.

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*The value of the autocorrelation function at its center ($\underline{r}$ = 0) is the integrated squared value of the entire image. This should be much greater than typical output values from the noise field.

Further applied research to implement and improve on these basic ideas is to be recommended. Because of the present availability of most of the technology needed for implementing our suggestions, the investment in equipment and time for such research should not be of major proportions.

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V. B. Schneider/by C. J. Byrne

1012-VBS-jdc V. B. Schneider

Attachment
References
Appendix A

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APPENDIX A

On the Design of Wiener Filters for Lunar Images

Figure 6 of reference (10) charts the power spectral densities of terrain altitudes of surfaces such as a grass runway, an area of Mare Cognitum, and the Bonito Lava flow in Arizona. The curves of these spectra all fall remarkably close to functions of the form

$$P_i(w) \approx \frac{K_i}{w^2} \tag{1}$$

Here, w is frequency in radians per meter, and $P_i(w)$ is a random-direction, one-dimensional Fourier spectrum over terrain i. In this section, we take the hypothesis that equation (1) is empirically correct for the lunar surfaces seen by Lunar Orbiter.

Suppose that we wish to find the power spectrum of surface <u>slopes</u> appearing in a given lunar scene. Let a(r) represent the altitude of a lunar surface as a function of displacement r from some origin. Then the surface slope is given by a'(r), the first derivative of altitude. In communication theory terms, taking the derivative of a(r) is like passing signal a(r) through a filter h(r) whose transfer function is

$$H(w) = jw \quad .$$

From equation (1), we have that $\Phi_{aa}(w)$, the power spectrum of altitudes, is of the form

$$\Phi_{aa}(w) = K_a/w^2 \tag{2}$$

By well-known results of linear systems theory, the power spectrum of slopes can then be found from $\Phi_{aa}(w)$:

$$\Phi_{a'a'}(w) = H(w)\ H(-w)\ \Phi_{aa}(w) \tag{3}$$

That is, the power spectrum of lunar surface slopes is of the form

$$\Phi_{a'a'}(w) \approx K_a \tag{4}$$

for all spatial frequencies of interest.

The brightness seen at an illuminated point of the lunar surface is a nonlinear, positionally dependent function of surface slope. A lunar surface photographic image that has been compensated for variations in illumination angle, viewing angle, and surface albedo has a brightness distribution that is a uniform function of surface slope. On that basis, it seems reasonable to believe that $S(\underline{w})$, the (fully corrected) two-dimensional brightness power spectrum of lunar images, is related directly to the power spectrum of lunar surface slopes. In particular, there is empirical evidence from equation (3) to suggest that $S(\underline{w})$ is of the same form as equation (4).

On the foregoing evidence, we can suggest a particularly simple form of the Wiener optimum filter for use in processing the lunar photographs. Let $F(\underline{w})$ represent the lens film modulation transfer function of the spacecraft camers, which can be measured in advance. $R(\underline{w})$ is the two-dimensional power spectrum obtained from $B(\underline{r})$, the image brightness distribution of a photometrically corrected lunar image. $S(\underline{w})$ is the actual power spectrum of lunar surface slopes, as discussed above. Then, the optimum two-dimensional Wiener filter is given by (5):[10,12]

$$H_{opt}(\underline{w}) = \left(\frac{|F(\underline{w})|^2\ S(\underline{w})}{R(\underline{w})}\right)\left(\frac{1}{F(\underline{w})}\right) \tag{5}$$

In (5), note that $F(\underline{w})^2$, $S(\underline{w})$, and $R(\underline{w})$ are real functions of $\underline{w}$. In addition, from (4), we have that

$$S(\underline{w}) \approx K_i \qquad (6)$$

for all spatial frequencies of interest. This mean that (5) can be rewritten in terms of its amplitude and phase functions as follows:

$$H_{opt}(\underline{w}) \approx \frac{K_i |F(\underline{w})|}{R(\underline{w})} \exp[-j\mu(\underline{w})] \qquad (7)$$

Here,

$$\mu(\underline{w}) = \arctan \frac{Im[F(\underline{w})]}{Re[F(\underline{w})]} \qquad (8)$$

It is useful to discuss the physical significance of (6): we observe that there is much more high-frequency detail in any lunar scene than can be recorded by one imaging camera. Imagine an experiment in which an orbiting satellite photographed the moon over some fixed location on the surface, under uniform lighting conditions. Several pictures are taken, each one twice as near to the surface as the previous one. Each such picture will be crammed with detail. But equation (4) above implies that there is no a priori way of telling from the photographs themselves which altitude they were photographed from. On the other hand, equation (4) does not imply that the power spectra $R(\underline{w})$ of these photographs will be identical. This is because $S(\underline{w})$ is a term in $R(\underline{w})$, and $S(\underline{w})$ may be an arbitrary constant which varies from scene to scene. Thus, the balance between signal and noise power contained in $R(w)$ changes from scent to scene.

On the basis of equation (7), we can outline one practical scheme for optimal noise suppression in received lunar imagery: the image is first processed to remove multiplicative effects, such as vignetting, and nonlinear effects, such as are detected in the film exposure calibration. By use of the optical bench, a film mask $M(\underline{w})$ is exposed whose brightness distribution in terms of coordinates $\underline{w} = (w_x, w_y)$ on the mask is given by $R(\underline{w})$. This mask is then contact printed on a second sensitized plate to give brightness distribution proportional to $1/R(\underline{w})$. An optical bench is set up in cascade having two Fourier planes. Into the first plane is inserted a mask which simulates the function

$$|F(\underline{w})| \exp(-j\mu(\underline{w})) , \tag{9}$$

and into the second Fourier plane is inserted the mask whose brightness distribution is of the form $1/R(\underline{w})$. The image used to prepare the $R(\underline{w})$ mask is placed on the input plane, and a sensitized plate in the output plane receives the filtered image. This filtered image should be corrected for additive system and film grain noise and for the effect of the film lens transfer function.

If received images for a particular lens of the Lunar Orbiter all yield similar processed masks corresponding to $R(\underline{w})$, a further processing economy could be achieved: only one mask would be needed to process all of the received imagery from a given lens film system of the Lunar Orbiter. There is some reason to believe that this situation may arise in practice: the author's experience with a Fourier analysis pattern recognition experiment indicates that most of the variation between optical targets in a class of similar patterns becomes evident from the phase components of those target's Fourier spectra. Thus, variation between lunar imagery brightness power spectra could well be minor.